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FIRM R&D GAMES WITH DIFFERING MANUFACTURING COSTS

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The paper considers an industry where competition is characterized as a two-stage game between the two firms in which the product reliabilities are determined before the (Cournot) quantities. Reliability is determined by R&D expenditure. The focus is on how competitive conditions in terms of manufacturing costs affect the firms' decision about optimal reliability. The main result of the paper is that the firm with lower manufacturing cost produces a more reliable product. However a reduction in a given firm's manufacturing cost only causes it to produce a more reliable product when the difference in costs between firms is low. Comparative static exercises suggest that reliability generally increases when customers have a higher reservation price for the product and a lower customer cost of product failure.

Research and development strategies are key to profitability for many firms. While R&D expenditures can affect the firm in many ways, the present paper focuses on the situation when R&D spending is used to increase the reliability of a firm's product. Consider an industry where competition is characterized as a two-stage game between the two firms in which the product reliabilities are determined before the (Cournot) quantities. Reliability is determined by R&D expenditure. The focus of the present paper is on how competitive conditions (in terms of manufacturing costs) affect the firms' decision about optimal reliability.

The paper is theoretical, the model having many formal similarities with the R&D/quality literature where quality is chosen first and then quantities are chosen in a Cournot-type game; see Neary and Leahy (2000), Jinji and Toshimitsu (2006), DeCourcy (2005), Haaland and Kind (2008, 2006), and Gretz, Highfill, and Scott (2009). These papers differ from the present paper in that their focus is on whether R&D should be subsidized rather than on the product quality (reliability) itself as the present paper does. With the exception of DeCourcy (2005), all of these papers essentially argue that R&D should be subsidized either because firms' decision making ignores aspects of social surplus like consumer surplus, (Jinji and Toshimitsu (2006), Haaland and Kind (2008, 2006), and Gretz, Highfill, and Scott (2009)) or intra-firm spillovers (Neary and Leahy (2000)). DeCourcy (2005), on the other hand, argues that allowing research cooperation between competing firms is superior to any subsidy policy.

The present paper draws particularly on Highfill and McAsey (2010) except that while the present paper neglects its dynamic considerations, reliabilities are endogenous for both firms as they were not in that paper. The present paper relies on numerical analysis of the theoretical model.

The main result of the paper is that the firm with lower manufacturing cost produces a more reliable product. However this only holds when the difference in costs between firms is small. Comparative static exercises suggest that reliability generally increases when customers have a higher reservation price for the product and a lower customer cost of product failure. (The exception is noted below.)

THE MODEL

Suppose there is a distribution of customer reservation prices for a perfect product where the reservation price is the highest price a potential customer is willing to pay for a perfect product. Reservation prices are assumed to be uniformly distributed on the interval (W,V). That is, W is the minimum reservation price for the product and is the maximum reservation price. Customers are indifferent between the products of the two firms when products are perfectly reliable (in which case the two firms will charge the same price). These distributional demand assumptions are similar to Herguera and Lutz (2003) and Gretz, Highfill, and Scott (2009); Haaland and Kind (2008, 2006) arrive at a similar (linear) derived demand function by assuming a quadratic utility function, while DeCourcy (2005), d'Aspremont and Jacquemin (1988), Brod and Shivakumar (1997), and Greenlee (2005) forthrightly assume linear demand with no income effects. For the ease of readers the present paper reviews the model setup of Highfill and McAsey (2010) with the exceptions noted above.

Our measure of product reliability is the probability that a product is judged by the customer to be of acceptable quality; this probability is denoted R_i for firms $i=1,2$. This notion of quality as product reliability (or the related concept of product failure) can be found in Daughety and Reinganum (1995), Gretz, Highfill, and Scott (2009), and Matthews and Moore (1987). Product failure imposes costs on the customer that are not reimbursed by the firm. This "cost to customers" of product failure is the parameter K, so the "expected cost of product failure" for a customer purchasing from the i^{th} firm is $(1-R_i)K$ since $(1-R_i)$ is the probability of product failure. Customers know the probability that any arbitrary unit will fail, but not whether the particular unit they purchase will fail. Customers whose reservation price v satisfies the following condition will purchase the product:

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$$v \geq P_1 + (1-R_1)K = P_2 + (1-R_2)K \qquad (1)$$

where P_i is the purchase price of the product from firm i. Customers are risk neutral in the sense that their buying decisions are based on price and expected customer cost of product failure. The expression $P_i + (1-R_i)K$ is conveniently called the "full quality price." While in general the firms' costs, qualities, and prices are not the same, for both firms to have positive sales it must be the case that the full quality price is the same for both firms. If this were not the case, customers would only buy from the firm with the lower full quality price. These assumptions imply linear demand functions N for the product

$$P_i = V - (1-R_i)K - \frac{V-W}{N}(Q_1 + Q_2) \qquad (2)$$

where N is the potential market size and Q_i is the quantity demanded of firm i's product.

Improvements in quality require research and development; the expenditure on R&D is $E_i \geq 0$ for firm i. Assume that such expenditure produces an improvement in the reliability of the firm's product, but is subject to diminishing marginal returns. Specifically,

$$E_i = k(R_i - R_{i0})^2 \qquad (3)$$

where $k > 0$, and defining $0 \leq R_{i0} \leq 1$ as the "default reliability" that would occur in the absence of any R&D expenditure. The assumption of a quadratic relationship between quality improvement and R&D spending which is independent of the quantity produced is found in Brod and Shivakumar (1997), d'Aspremont and Jacquemin (1988), Greenlee (2005), Herguera and Lutz (2003), Haaland and Kind (2006, 2008) and Gretz, Highfill, and Scott (2009). Recall that R_i is a probability and so is between zero and one, while the expenditure on R&D is typically rather large and certainly never less than one. Therefore the constant k needs to reduce R&D expenditures by several orders of magnitude and is typically a large number. Finally, although for the sake of simplicity we refer to E_i as R&D expenditure, it is really the component of expenditure which varies with reliability. There would normally be many fixed-cost R&D expenditures.

In addition to R&D costs, each firm has a per unit manufacturing cost of mc_i. It is assumed that the units of the product that fail are returned by the customer and replaced (or if repaired that the repair cost is the same as the replacement cost). Thus defining

$$c_i = mc_i + (1-R_i)mc_i \qquad (4)$$

the total manufacturing costs are $c_i Q_i$ because the manufacturing cost of the original units is $mc_i Q_i$; the (expected) cost of replacing or repairing the defective units is $(1-R_i)mc_i Q_i$, where $(1-R_i)Q_i$ is the expected number of defective units.

Firm profits can now be defined as

$$\Pi_i = (P_i - c_i)Q_i - E_i \qquad (5)$$

recalling equations (2)-(4). The firms play a two-stage game where the product reliabilities are determined before the (Cournot) quantities. Solutions are computed using generalized backward induction. Therefore, the quantity decisions are computed by solving the first order conditions $(\partial \Pi_i / \partial Q_i = 0)$. The results are substituted back into the objective function and the reliabilities found by solving the first order conditions $(\partial \Pi_i / \partial R_i = 0)$. The parameter values for the numerical results that follow are $V = 200, W = 100, K = 100, mc_1 = 100, \text{ and } k = 150{,}000$.

Thinking about the demand curve first, notice that with these parameters the range of reservation prices is 100, the range being moved up the axis so that the minimum reservation price is not zero. There is nothing special about the choice of 100, we just wanted the same order of magnitude for all parameters, except for k which as mentioned above needs to be orders of magnitude larger. This exact value of k was chosen so that the reliabilities seem reasonable; that is, in the range between 90% and 100%. The focus of this paper is on manufacturing costs and so the graphs reported in the next section serve as a kind a sensitivity analysis for differing relationships between the manufacturing costs of the two firms. See the discussion below. Although not reported here for brevity, we have done the same analysis for $mc_1 = 90$ and $mc_1 = 110$ getting results substantially similar to Figures 1-4.

THE RELATIONSHIP OF RELIABILITY TO MANUFACTURING COST ADVANTAGE

The focus of the present paper is on differences in marginal costs between firms. Suppose now that the marginal cost for firm 1 is simply $mc_1 = 100$. Define

$$\text{marginal cost ratio} = \frac{mc_2}{mc_1} = \rho_{MC}.$$

That is, firm 2's costs are greater than firm 1's if and only if the "marginal cost ratio" $\rho_{MC} > 1$. The relationship between the marginal cost ratio parameter and firm reliabilities is shown in Figure 1.

FIGURE 1

Reliabilities as a Function of the Marginal Cost Ratio

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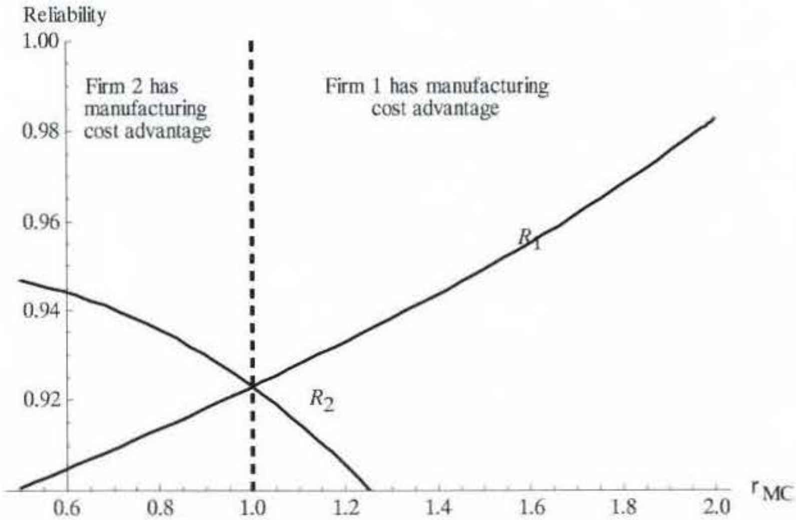
FIGURE 1

Reliabilities as a Function of the Marginal Cost Ratio



To interpret Figure 1, note that the solution of the firm's game is a function of ρ_{MC}. The manufacturing costs for firm 1 are held constant the manufacturing costs for firm 2 vary. Figure 1 and all the figures to follow essentially report comparative static results. When, for example, $\rho_{MC}=.5$, firm 2 has the manufacturing cost advantage with a manufacturing cost of 50 dollars per unit as compared to firm 1's manufacturing cost of 100 dollars per unit. When $\rho_{MC}=2$, on the other hand firm 2 has a manufacturing cost of 200 dollars per unit. Thus the right side of the figure ($\rho_{MC}>1$) is when firm 1 has the manufacturing cost advantage while the left ($\rho_{MC}<1$) is when firm 2 has the manufacturing cost advantage. At $\rho_{MC}=1$ the manufacturing costs are the same and reliabilities are the same. For short hand we will say that on the right, firm 1 has a manufacturing cost advantage or simply a cost advantage; on the left, firm 2 has the cost advantage.

The first result of the paper is that the firm with the manufacturing cost advantage will produce a higher quality product. Noticing that the R_1 curve is concave up (barely) and the R_2 concave down, a change in the marginal cost ratio has a "more than linear" effect on the two reliabilities.

From the numerical example above notice that on the right side of $\rho_{MC}=1$ the average of the two manufacturing costs is above firm 1's, while on the left it is below. Algebraically, this is

$$\frac{mc_1+mc_2}{2}=mc_1\left(\frac{1+\rho_{MC}}{2}\right) \quad \begin{cases} >mc_1, & \rho_{MC}>1 \\ <mc_1, & \rho_{MC}<1 \end{cases}$$

When the average is "high" (the right hand side of the figure) an increase firm 1's manufacturing cost advantage (i.e., an increase in the marginal cost ratio) causes the two reliabilities to diverge more than they would if the curves were linear. When the average is "low" (on the left) an increase in firm 2's manufacturing cost advantage (a decrease in the marginal cost ratio) causes the reliabilities to also diverge, but less than they would if the curves were linear.

The results reported in Figure 1 will be called the "base" case. The next three figures are also comparative static experiments. They explore the effect on reliability of changing the marginal cost ratio and one other parameter. In the figures that follow the base case is the solid line; the effect of the change in the parameter of interest is shown by a dashed line.

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FIGURE 2

Reliabilities as a Function of the Marginal Cost Ratio: Customer Valuation

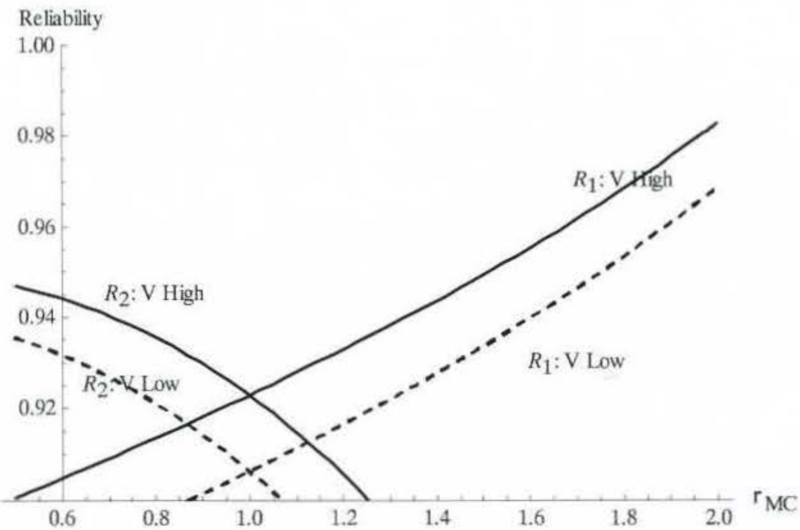


Figure 2 shows the effects of a reduction in the value that customers place on the product. Specifically, while in the base case the range of reservation prices was from $W=100$ to $V=200$ dollars, in the "low" case of Figure 2 the range is from $W=50$ to $V=150$ dollars. These results suggest that as customers value the product less firms respond by producing a less reliable product.

FIGURE 3

Reliabilities as a Function of the Marginal Cost Ratio: Customer Cost of Failure

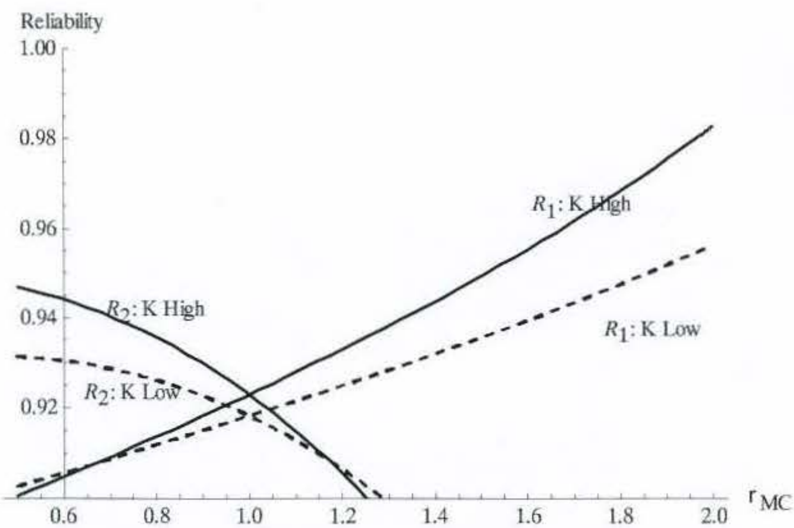
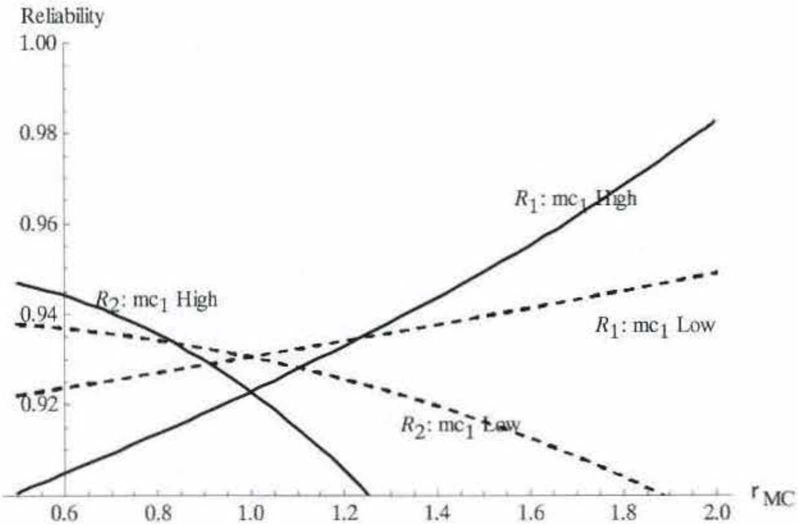


Figure 3 shows the effect of a reduction in the customer cost of product failure from $K=100$ dollars in the base case to $K=50$ dollars. Generally, as customers are less damaged by product failure firms respond by producing a lower quality product. But notice the anomaly of the reliability of firm 2 when its manufacturing costs are quite high. (The R_2 curves actually intersect.) Future work might further investigate this result.

FIGURE 4

Reliabilities as a Function of the Marginal Cost Ratio: Absolute Costs



The interpretation of Figure 4 is slightly tricky. The question is: what happens if the marginal manufacturing costs change? The base case (solid lines) is as explained above. The dashed lines change the marginal manufacturing cost of firm 1 to 50 dollars. Thus for example, when $\rho_{MC} = .5$ in the base case $mc_1 = 100$ and $mc_2 = 50$. For the dashed lines, at the same $\rho_{MC} = .5$ now $mc_1 = 50$ and $mc_2 = 25$. For all marginal cost ratios, lower overall manufacturing costs (dashed lines) lead to a smaller difference in reliabilities between firms reliabilities as compared to the base case. Further, considering the marginal cost ratios "near" $\rho_{MC} = 1$ both firm's reliabilities are higher than in the base case. As long as the firms' manufacturing costs are "similar" (i.e., $\rho_{MC} \approx 1$) lower overall costs lead to higher reliabilities. But when the marginal cost ratios are "farther" from $\rho_{MC} = 1$ the firm with the cost advantage has a higher reliability with the lower absolute costs. For example, on the far right where firm 1 has a larger cost advantage the reliability when its costs are low (the dashed line) is actually lower than for the base case. While on the far right dashed line for firm 2 is higher than the solid line of the base case. So when firms' manufacturing costs are very dissimilar, a reduction in its own marginal cost (dashed line compared to solid on the far right) leads the firm with the cost advantage to optimally produce a less reliable product. In summary, a reduction in a given firm's manufacturing cost only causes it to produce a more reliable product when the difference in costs between firms is low. When the difference in costs is high a firm with a manufacturing cost advantage will use a reduction in its marginal cost as the occasion to actually produce a less reliable product.

CONCLUSION

The theoretical exercise of the present paper considers the effects of manufacturing cost advantage on a firm's R&D expenditures, or equivalently in our model, on the quality of the product. The predictions of our analysis are sometimes straightforward. The firm with the manufacturing cost advantage will produce the more reliable product. But some of the predictions of the model are not so simple. It is not necessarily the case that a reduction in a given firm's manufacturing cost will cause it to produce a higher quality product. There is a sense in which a profit maximizing firm sometimes will take advantage of a reduction in its own manufacturing cost by actually doing less R&D—and thus producing a lower quality product.

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